LEUKOS

The Journal of the Illuminating Engineering Society

ISSN: 1550-2724 (Print) 1550-2716 (Online) Journal homepage: https://www.tandfonline.com/loi/ulks20

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To cite this article: Anya Hurlbert & Christopher Cuttle (2020) New Museum Lighting for People and Paintings, LEUKOS, 16:1, 1-5, DOI: 10.1080/15502724.2019.1676019

To link to this article: https://doi.org/10.1080/15502724.2019.1676019

Published online: 04 Nov 2019.

LEUKOS
2020, VOL. 16, NO. 1, 1–5
https://doi.org/10.1080/15502724.2019.1676019

EDITORIAL

New Museum Lighting for People and Paintings

Of all lighting applications, museum lighting is uniquely challenging. The lighting must not only reveal the visual detail and emotional power of the artwork to the viewer, but also protect and preserve its content and integrity for the future. The lighting also contributes critically to the entire aesthetic and affective experience of the museum visitor. Many people therefore have strong stakes in the physical properties of the illumination, as well as its look and feel: exhibition curators, conservators, sponsors, lenders, press officers and relationship advisers. Others have equally important stakes from practical considerations of energy efficiency, cost, and sustainability: exhibition planners, museum directors and trustees, building services and security staff. The lighting designer, in turn, must work with the multiple resulting demands and constraints to create a setting that is vital to the short- and long-term success of the museum. These complementary considerations are summarised in this special issue by Thomas Schielke (2019), who explores the role of light in creating vastly varying atmospheres, depending on the artworks' content and artists' intentions, either unifying the works with the space or objectifying them, immersing or isolating the viewer, expanding or focussing the view.

The biggest challenge for museum lighting today, though, is keeping up with the concurrent rapid changes in light technology and the understanding of how light affects human behavior. Just as biologists are discovering new pathways in the brain that mediate people's response to light both visually and non-visually—modulating mood, health, alertness, perception, and performance (Bauer et al. 2018; Spitschan 2019; Vandewalle et al. 2009)—engineers are developing new smart lighting technologies that can modulate illumination spectra in real time to fit the time of day, the place, the people, and the task at hand (Chew et al. 2016; Hertog et al. 2015; Llenas and Carreras 2019; Llenas et al. 2019). Behavioral studies in the workplace, classroom and clinic have demonstrated the effects of spectrally varying light exposure on mood, cognitive function, visual comfort and the sleep-wake cycle (e.g. Choi et al. 2019; Figueiro et al. 2017). Yet museums—where artworks and artifacts need the right light to be seen, appreciated, and conserved, and viewers often want to experience deep feeling as well as to learn or be entertained—should be at the forefront in capitalising on these new technical and scientific advances.

In accord with the interdisciplinarity needed to integrate and optimise these multiple developments, a richly varied group of individuals came together in London for the 2017 International Museum Lighting Symposium and Workshops (MLSW2017) (Andrikopoulos 2017): conservators, curators, architects, lighting engineers, conservation scientists, vision scientists, psychologists, lighting designers, art historians, and more, from museums, academia, and industry, world-wide.

The papers presented at MLSW2017, as do the papers collected in this special issue, capture the considerations of a research field and practice in flux. Museum lighting is no longer at a major crossroads, trying to decide whether to travel away from traditional incandescent and fluorescent lamps towards solid state lighting, but has already moved down that route, and is now seeking out the optimum paths through an ever-branching network. Already, several projects in high-profile institutions have demonstrated the potential of solid-state lighting, for example, the relighting of the Sistine Chapel with optimised LED lighting (Schanda et al. 2016), and the lighting of a polychrome sculptures with sets of color-tunable LED lights in the Art Institute of Chicago (Ketra, n.d.).

As Garside et al. (2017) observe, the main drivers for the move towards LED lighting in museums have been cost savings and energy efficiency, and given the huge improvement in these that LED lighting brings relative to older light technologies, there has been less focus on smaller differences between different LED systems,

Gold Open Access for this manuscript was supported by the 1st International Museum Lighting Symposium & Workshops. London, England. September 2018.

particularly with respect to the potential for enhancing visibility or colour appearance, or indeed the visitor's experience.

In this issue, Richardson et al. (2019) delve into the issues underlying the LED lighting movement. They note that, in theory, relighting English Heritage buildings with LEDs might reduce monetary and energy expenditure by 85% compared to the costs of the existing UV-filtered tungsten halogen sources. Yet they reiterate the need to ensure that LED relighting will not adversely affect vulnerable pigments, paints, and paper. Given the background of concern over the damage potential of light at 450nm—the emission peak of phosphor-based white-light LEDs—Richardson et al. (2019) specifically assessed the impact of such LED lighting on the stability of yellow pigments which are both particularly sensitive to short-wavelength light and also typically used in English Heritage collections. Using an accelerated ageing paradigm, Richardson et al. (2019) demonstrate that, in comparison with tungsten halogen lights, two types of LED lighting with short-wavelength power peaks elicit larger colorimetric shifts and chemical degradation in certain pigments.

Yet the rapid pace of development in LED lighting technologies means that short-wavelength peaks need not be an invariant feature of LED-based lighting. Narrow-band LEDs are now available with peaks covering the whole visible spectrum, making it possible to create multi-channel LED light engines whose output spectra may be sculpted to almost any desired shape. Although such spectrally tuneable multi-channel LED lamps are not yet widely accessible commercially, they are embedded in multiple research areas and their cost is steadily coming down (see e.g. Durmus et al. 2018; Llenas and Carerras 2018; Nascimento and Masuda 2014; Wei et al. 2018). Smart control systems are also under intense development, and being integrated with other smart building systems.

In this special issue, Durmus, Abdalla, Duis and Davis (2018) foresee a future in which these innovations in lighting technology are harnessed to tune illumination spectra to the reflectance properties of individual artworks (or parts thereof), to minimise damage and maximise colour rendering and discriminability. Indeed, as Schielke (2019) describes in this issue, the prospects for tuning light spectra are not limited to these material aims; tuning the light in targeted zones may generate hyperrealistic colors and thereby enhance the artist's concept. Building on previous studies that aimed primarily to improve energy efficiency, Durmus et al. (2018) demonstrate the use of computational techniques (in particular, a multi-objective genetic algorithm) to optimise light spectra under the triple constraints of minimal energy absorption, maximal colour fidelity, and minimal energy consumption. The algorithm generates optimal light spectra made by combining outputs of seven narrow-band LEDs for each of 5 different oil paints typical of Old Master artworks. Their findings indicate that significant reductions of both absorbed radiant energy and lighting power consumption may be achieved (for example, a 47% decrease relative to incandescent illumination, for blue paint) without inducing perceptible color shifts.

Colour fidelity and colour quality measures give objective indicators of how light might affect people's perceptions, but these do not tell the whole story. What people subjectively prefer in real settings may be influenced by multiple factors, from physical characteristics of the illumination spectra, to personal physiology and history, to the semantic and emotional content of the artworks on display (Padfield et al. 2016). For lighting, the overall lux level plays a critical role in driving preferences, as previous studies have shown (e.g. Zhai et al. 2015; 2016).

Given that museum lighting standards limit overall lux to much lower levels than typically used in conservation work or lighting research (20-50 vs. 200-500 or well above), it is important to study subjective responses at those levels, to understand fully the effects of light in museum settings. In this issue, Wei, Bao and Huang (2018) do just this. They note that specification of color rendering generally does not take account of illumination level, and examine directly how preferences for color rendering vary with illuminance level. Wei et al. (2018) also take advantage of the tuneability of multi-channel LED sources, using a 7-channel light engine to create 4 nearly metameric spectra of the same correlated colour temperature but different colour rendering characteristics, quantified by the IES TM-30-15 colour gamut measure R_g. Using a forced-choice psychophysical paradigm, Wei et al. (2018) measure subjective preferences for the appearance of an oil painting under these 4 light spectra at two illuminance levels, 20 and 500 lux. Indeed, as the Hunt effect would predict, people prefer higher saturations (larger color gamuts) at lower illuminances.

Yet lux levels do not alone determine preference, nor indeed the full subjective experience of the viewer. The perceived brightness and colour of surfaces depend on their spatial and temporal context; contrast is fundamental to visual perception. As Shielke (2019) observes in this issue, context and contrast are also fundamental to creating distinct lighting atmospheres, foregrounding dark paintings against bright architectural white, or spotlighting works as the peripheral space "recedes into darkness", intensifying their impact. In the 'The Sacred Made Real' (National Gallery, London 2009-10), polychrome sculpted figures arose shining from dimly lit alcoves, like spiritual guides. Such dramatic manipulation of lighting enables communication between the work and viewer that goes beyond material appearance. Building on earlier work examining the role of CCT in determining preferences for paintings (Nascimento and Masuda 2014), work in this special issue by Feltrin, Leccese, Hanselaer and Smet (2019) quantifies the effects of different background lightnesses, illumination CCTs and lux, and source configuration on subjective responses to paintings, including impressions of warmth, vividness, brightness and overall appreciation. Of these factors, only illumination CCT elicits significant variation in these subjective qualities, but the isolation of the studied paintings inherent to the viewing setup might have minimised the background lightness effects.

Feltrin et al. (2019) mixed an ambient fluorescent illumination with a tuneable 4-channel LED spotlight, creating spatially heterogeneous lighting ranging in color temperature from cool to warm. Combining diffuse and directional lights with varying color temperatures effectively recreates natural daylight, which is a mixture of sunlight and skylight. The spatial and spectral characteristics of daylight are further modulated by atmospheric conditions including cloud, fog and haze, as well as by geographical location, season, weather and time of day (Webler et al. 2019; Woelders et al. 2018). The human visual and non-visual responses to light evolved under daylight, and there is evidence that brain pathways are optimised to follow natural variations in daylight (Aston et al. 2019; Lafer-Sousa et al. 2012; Pearce et al. 2014). Artists too have historically preferred to paint under daylight. An obvious question, then, is why not use only daylight itself to illuminate museums?

This human connection to daylight perhaps underpinned resistance to installing new lighting technology in museums in the late 19th century. It was not until 1934 that the National Gallery, London inaugurated electric lighting, more than 50 years after the Savoy Theatre in London became the first public building in the world to be lit entirely by electricity, using Joseph Swan's incandescent lightbulbs. Artificial lighting also has traditionally meant static lighting, fixed in spectrum and space. Daylight, in contrast, changes continuously, on short and long timescales. As one museum director observed, natural lighting in museums encourages people not just to visit, but to visit and re-visit, to experience changes in view as the light naturally brightens and dims over time, creates shadows and highlights, reveals new tonalities, and directs or diffuses the gaze.

This dynamism of daylight is particularly revealing for sculpture; changes in shading over time elicit a deeper understanding of three-dimensional shape. Hence, in ARUP's lighting design for the New Acropolis Museum, as Florence Lam explained in her keynote talk at MLSW2017 (Lam 2017), the aim was to bring daylight into the interior space, recognising that the ancient sculptures were "created to be seen outdoors and to be illuminated by the subtle changes in light throughout the day. These variations enhance the rich differentiations of the marble surfaces and the viewer's appreciation of the sculpture."

More broadly, the challenge now for museum lighting is how to harness daylight and integrate it with new lighting technologies. Historic solutions allow natural light to enter where skylights and windows permit, regulated by mechanical blinds (as in the National Gallery, London), and mixing it with artificial light to achieve balanced color temperatures and light levels. Smart systems based on tuneable LED lighting will enable dynamic lighting with enormous flexibility; these might be preprogrammed sequences designed to prevent that component of museum fatigue which might result from exposure to dim reddish light at midday (Sahin and Figueiro 2013), or to simulate the artist's native environment or recreate a candlelit chapel at night, or to direct the viewer's attention to surfaces or concepts. Such systems will enable daylight spectra to be recorded from rooftop locations and played back through the luminaires in real time (Llenas and Carerras 2018; Llenas et al. 2019) with the potential for removing particularly toxic wavelengths first; at the same time, integrated light sensors may monitor light exposure specific for each painting. Knowledge of the effects of varying light spectra on different substrates, from in-depth studies such as Dang et al.'s (2019) Raman spectroscopic assessment of the molecular structural changes induced by light exposure in traditional Chinese silk and paper, will be paramount to enable lighting designers to take full advantage of this extended range of control.

Our hope is that from the interdisciplinary meeting of minds and exchange of theory, practice and ideas, as exemplified by research presented in this special issue and at MSLW2017, museums will be spurred to lead the adoption of new lighting standards and practice. These should both codify the new understanding of the viewer's biological and psychological response to light—how light affects seeing and feeling—using, for example, a circadian stimulus metric (e.g. Rea and Figueiro 2018), and fully exploit innovations in smart lighting technology that preserve, protect, and release the full perceptual and emotional power of the works to the viewer.

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